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The Effect of Moisture in the Air on the Operation of Gas Engines and Air Compressors

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THE EFFECT OF MOISTURE IN THE AIR ON THE OPERATION OF GAS ENGINES AND AIR COMPRESSORS

BY

CHAUNCEY BRISTOL OLIVER

THESIS

FOR THE

DEGREE OF BACHELOR OF SCIENCE

IN

MECHANICAL ENGINEERING

COLLEGE OF ENGINEERING

UNIVERSITY OF ILLINOIS

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June 1, 1912. 190

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Chauncey Bristol Oliver

ENTITLED The Effect of Moisture in the Air on the Operation of Gas Engines and Air Compressors

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science in Mechanical Engineering.

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THE EFFECT OF MOISTURE IN AIR ON GAS ENGINE AND AIR COMPRESSOR PRACTICE.

I. INTRODUCTION.

As a general thing air is considered dry. This is an erroneous conclusion because the evaporation of the water on the surface of the earth impregnates the air with a certain amount of water vapor. While the weight of this water vapor is small in comparison with the weight of the air, yet if accurate calculations are to be made in problems that involve the use of air, the moisture in it must be taken into consideration. This moisture in the air is measured by the per cent of humidity, which is the ratio of the actual amount of moisture in the air to the amount that the same volume of air could hold at the same temperature if it were saturated with water vapor. One pound of saturated air at 90° F. would contain 14.4 grains of moisture; at ten degrees below zero it would contain 0.29 grains. These figures show that there is an appreciable amount of water vapor in the air, and, if correct analysis of the performance of gas engines and air compressors is to be made, this moisture in the air must be taken into consideration.

It is the object of this thesis to show the effect this moisture has on gas engine and air compressor practice.

II. THE EFFECT OF WATER VAPOR ON GAS ENGINE PERFORMANCE.

The effect of water vapor on gas engine performance is best illustrated by a concrete example. Assume that for M lb. of fuel entering the cylinder of an engine of the Diesel type, there is required 1 lb. of dry air at 90° F. and at atmospheric pressure. From the universal gas law, the volume of the air can be found as follows:

$$P\ V = M\ B\ T$$

$M = 1$ $\qquad T = 90+460 = 550^\circ$ absolute temperature

$B = 53.34$ $\qquad P = 14.697$ absolute pressure

$$V = \frac{B\ T}{P} = \frac{53.34 \times 550}{14.697 \times 144} = 13.86 \text{ cu. ft.}$$

Now if saturated air at the same temperature and pressure be placed in a cylinder of 13.86 cu. ft. content, the pressure of the mixture is 14.697 lb. per sq. in. From Dalton's law, considering the air and water vapor as two gases, the pressure of the mixture minus the pressure of the water vapor gives the pressure of the dry air. The pressure of the vapor can be obtained from any table of saturated steam. For 90° F. the value of p is 0.695 lb. per sq. in. The pressure of the air is therefore 14.697 - 0.695 = 14.001 lb. per sq. in.

Again calculating from the gas law,

$$M = \frac{P\ V}{B\ T} = \frac{14.001 \times 144 \times 13.86}{53.34 \times 550} = 0.952 \text{ lb. of air,} \quad (I)$$

which is the actual weight of air in the cylinder. Instead of one pound of dry air, as in the first case, there is only in reality 0.952 lb., showing a loss of 0.048 lb. of air displaced by the moisture. This decrease is due solely to the moisture in the air,

so that if the cylinder is designed to require one lb. of air for combustion on a basis of dry air, when the air is wet leaving only 0.952 lb. dry air actually in the cylinder, there will not be complete combustion on account of this 0.048 lb. deficit.

Thus to get the actual amount of wet air required, these preceding calculations must be made. To simplify this work the problem may be taken up in a little different way. Considering the air and vapor as a gaseous mixture, this mixture has a constant, which we will denote by B_m. As the water vapor content in the air changes, the constant B_m of the mixture also changes.

An expression for this constant B_m may be found by the following method. M_1 lb. of air at a partial pressure p' and M_2 lb. of water vapor with partial pressure p" are contained in a volume V. Then assuming as before that the gas law may be applied to the vapor, we have

$$p' V = M_1 B_1 T \qquad (1)$$

$$p'' V = M_2 B_2 T \qquad (2)$$

$$\frac{p''}{p'} = \frac{M_2}{M_1}\frac{B_2}{B_1} \qquad (3)$$

Let

$$\frac{M_2}{M_1} = z, \text{ and } \frac{B_2}{B_1} = e;$$

then from (3)

$$\frac{p''}{p'} = \frac{p''}{p - p''} = ez \qquad (4)$$

whence

$$p'' = p\,\frac{ez}{1 + ez}, \qquad p' = p\,\frac{1}{1 + ez} \qquad (5)$$

Adding the members of (1) and (2), we obtain

$$pV = (M_1B_1 + M_2B_2)\,T$$

$$= M_1B_1(1 + ez)\,T$$

$$= \frac{M_1B_1}{M_1 + M_2}(1 + ez)(M_1 + M_2)\,T \qquad (6)$$

The constant B_m of the mixture is, however, given by the equation

$$pV = (M_1 + M_2)\,B_m\,T \qquad (7)$$

Hence, comparing (6) and (7), we have

$$B_m = B_1 \frac{M_1}{M_1 + M_2}(1 + ez) = B_1 \frac{1 + ez}{1 + z} \qquad (8)$$

Taking the molecular weight of water vapor as 18, we have

$$B_2 = \frac{1543}{18} = 85.72$$

$$e = \frac{B_2}{B_1} = \frac{85.72}{53.34} = 1.61$$

Referring back to the example in the preceding paragraph, the weight of air per cubic foot is $\frac{0.952}{13.86}$ = 0.068786 lb., while from the steam table the weight of a cubic foot of steam at 90° is 0.002121 lb. Hence,

$$z = \frac{M_2}{M_1} = \frac{0.002121}{0.068786} = 0.031.$$

Substituting the value of B_1, e, and z in (8), the B_m of the mixture is

$$B_m = 53.34 \times \frac{1 + 1.61 \times 0.031}{1 + 0.031} = 54.313$$

Taking the same conditions as before but considering the mixture as one gas with a constant $B_m = 54.313$, we have for the weight of the mixture

$$M = \frac{14.697 \times 144 \times 13.86}{54.313 \times 550} = 0.9814 \quad (II)$$

But

$$\frac{M_m}{M_1} = \frac{B_1}{B_m} \qquad M_m = M_1 \times \frac{B_1}{B_m} = 1 \times \frac{53.43}{54.313} = 0.9814 \quad (III)$$

Hence, the weight of air and contained water vapor in the given volume is 0.9814 lb.

$$\text{The weight of the steam} = \frac{\text{Volume}}{\text{Volume of 1 lb. vapor}} = \frac{13.86}{478.4} = 0.0294 \text{ lb.}$$

The weight of the air and vapor minus the weight of the water gives the weight of the dry air in the given volume.

$$0.9814 - 0.0294 = 0.952$$

This checks with the equation (I) page 2. Therefore, to get the actual weight of wet air, multiply the weight of the amount necessary for combustion by the ratio $\frac{B_m}{B_1}$. Then if we know the amount of dry air M_1 that we wish in the cylinder, the temperature, and the humidity of the air to be used, we can calculate the weight M_m of moist air from the equation. The weight of dry air is then obtained by subtracting from the weight of the mixture the weight of the vapor present as determined from the steam table.

$$M_m = M_1 \times \frac{B_m}{B_1}$$

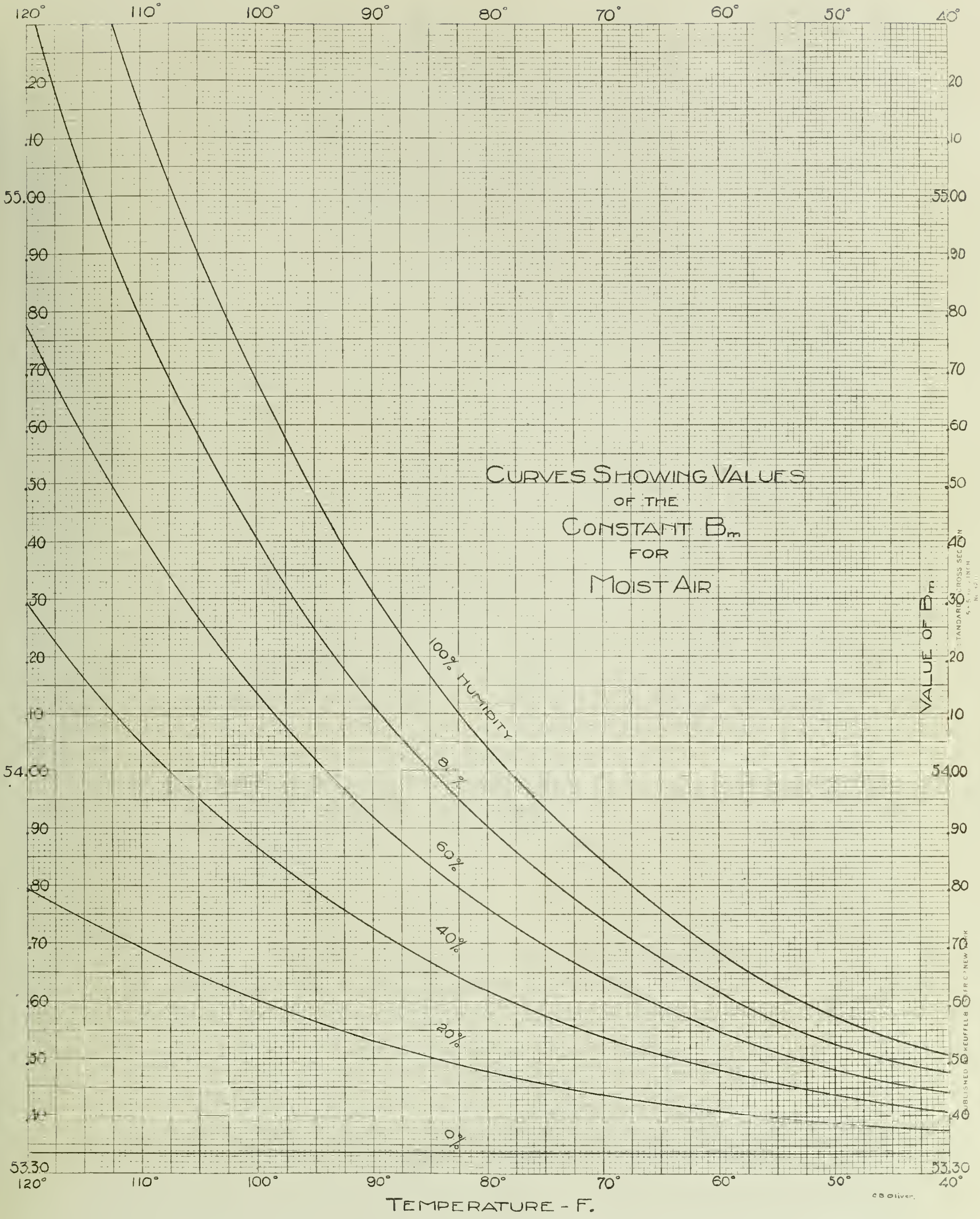
III. VALUES OF B_m.

Since values of B_m are extremely useful in a variety of problems it is advisable to construct a graphical chart from which such values may be found without calculation. The following table gives values of B_m for various percentages of humidity, between the limits of 40° F and 180° F.

TABLE I

Values of B_m with varying Temperatures and Humidity

	Humidity				
Temperature	100°	80°	60°	40°	20°
40°	53.506	53.475	53.441	53.406	53.373
50°	53.574	53.527	53.482	53.439	53.390
60°	53.686	53.618	53.351	53.482	53.411
70°	53.842	53.746	53.640	53.539	53.438
80°	54.040	53.900	53.760	53.618	53.479
90°	54.313	54.113	53.920	53.725	53.531
100°	54.680	54.406	54.136	53.869	53.604
110°	55.154	54.890	54.416	54.051	53.694
120°	55.781	55.250	54.778	54.293	53.796
130°	56.594	55.905	55.248	54.598	53.961
140°	57.648	56.731	55.850	54.986	54.150
150°	59.024	57.796	56.613	55.491	54.375
160°	60.806	59.150	57.590	56.099	54.674
170°	63.144	60.910	58.827	56.857	55.060
180°	66.229	63.334	60.402	57.860	56.994



CURVES SHOWING VALUES OF THE CONSTANT B_m FOR MOIST AIR

The accompanying chart shows humidity curves plotted to temperature ordinates, with values of B_m as abscissa. To illustrate the use of the curves let us take an example. Assume that we have air at temperature of 80° F., 70 per cent humidity, and atmospheric pressure. Run up the temperature column on the chart until the horizontal line of 80° F. temperature is reached. Follow this line across to the 70 per cent humidity curve. Then follow vertically down and read the value of B_m, which is 53.83. $B_1 = 53.34$. The ratio of the weight of a given volume of dry air to the weight of moist air under the same conditions of pressure and temperature is

$$\frac{B_m}{B_1} = \frac{53.83}{53.34} = 1.0092.$$

Hence if a given cylinder volume contains M lb., of dry air it will under the conditions stated contain

$$M \times \frac{1}{1.0092} = 0.99 \text{ lb. of}$$

mixture of air and vapor, and for the dry air present this weight must be still further reduced by the weight of the water vapor.

IV. THE EFFECT OF MOISTURE IN AIR COMPRESSION.

The effect of moisture in air compression may be considered under three conditions.

(1) Air compression when the air is dry.

(2) The effect of normal humidity in the air.

(3) The effect of introducing water into the compressor cylinder.

The question to be determined is to what extent the work of compression and expulsion, that is, the work represented by the indicator diagram, is influenced by the presence of normal moisture or excess of water in the air.

Case (1) Dry Air. Let us assume that we have one pound of dry air at 70° F., atmospheric pressure, and wish to compress it to 150 lb. per sq. in.

The volume before adiabatic compression is obtained from the relation

$$V_1 = \frac{M_1 B T_1}{p_1} = \frac{53.34 \times 530}{14.7 \times 144} = 13.4 \text{ cu. ft.}$$

The work represented by the ideal indicator diagram is given by

$$W = \frac{k}{k-1} \cdot p_1 V_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} - 1 \right]$$

$$= 3.5 \times 14.7 \times 144 \times 13.4 \left[\left(\frac{150}{14.7}\right)^{0.2857} - 1 \right]$$

$$= 93180 \text{ ft. lb.}$$

Case (2) Air with normal moisture. In this case we may consider the fluids simply as a gaseous mixture with a constant B_m, which may be determined from the curves for B_m.

From the general theory, the work of the cycle is given by

$$W = \frac{k}{k-1} \; p_1V_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} - 1 \right]$$

Let the symbols with subscript m denote the mixture of air and moisture, and the symbols without subscript dry air. For dry air we have

$$k = \frac{C_p}{C_v} = 1.4$$

and for the mixture

$$k_m = \frac{C_{pm}}{C_{vm}} \quad ,$$

which may be different from k. Initial pressure p, and volume v, final pressure p_2 and volume v_2 are constant. In any case, however,

$$C_p - C_v = AB,$$

applying equally well to dry air and to mixtures.
We have then for the mixture

$$C_{pm} - C_{vm} = AB_m$$

or

$$C_{vm} \; (k_m - 1) = AB_m$$

If $z = \frac{M_2}{M_1}$, the ratio of steam to air, then

$$C_{vm} = \frac{Cva + zC_{vs}}{1 + z}$$

where C_{va} = the C_v of air, and C_{vs} = C_v of steam in the mixture.

Taking $C_{va} = 0.17$, and $C_{vs} = 0.30$, the ratio $\frac{C_{vs}}{C_{va}} = 1.75$. Hence

$$C_{vm} = \frac{1 + 1.75\ z}{1 + z} \cdot C_{va}$$

Also

$$B_m = B\,\frac{1 + 1.61z}{1 + z}$$ from equation (8)

page

Substituting these values for C_{vm} and B_m

$$k_m - 1 = \frac{AB_m}{C_{vm}}$$

$$= \frac{1 + 1.61\ z}{1 + 1.75\ z} \cdot \frac{AB}{C_{va}}$$

$$= \frac{1 + 1.61\ z}{1 + 1.75\ z} \cdot (k - 1)$$

Now let

$$a = \frac{1 + 1.61\ z}{1 + 1.75\ z}$$

Then

$$k_m - 1 = a(k - 1)$$

And

$$k_m = ak + (1 - a)$$

$$= ak + \frac{0.14\ z}{1 + 1.75\ z}$$

Hence

$$\frac{k_m}{k_m-1} = \frac{ak + 1 - a}{ak - a}$$

$$= \frac{k - (1 - \frac{1}{a})}{k - 1}$$

$$= \frac{k + \frac{0.14z}{1 + 1.61z}}{k - 1}$$

For saturated air $z = 0.0052$ at 40° F , $\frac{k_m}{k_m-1} = 3.5018$

$= 0.0157$ at 70° F $= 3.5051$

$= 0.6559$ at 180° F $= 3.6120$

Since

$$\frac{k}{k-1} = \frac{1.4}{0.4} = 3.5,$$

it appears that $\frac{k_m}{k_m-1}$ differs but very little from $\frac{k}{k-1}$, especially at normal temperatures. Hence the work per cycle is changed only slightly by the presence of moisture in the air.

Example. The difference may be shown by taking the data given in Case (1), using the same volume, 13.4 cu. ft., and comparing the result with that obtained in Case (1). Assume that this air is saturated. From the table of saturated steam under 212° F at 70° we get the weight of one cu. ft. of saturated steam as 0.001145 lb. and a pressure of 0.3625 lb. per sq. in. The pressure of air then, from Dalton's law, is 14.697 - 0.3625 = 14.334 lb. per sq. in. Then the weight of one cu. ft. of air can be found by the equation

$$pV = MBT$$

or

$$M_{air} = \frac{144 \times p'}{B\ T}$$

$$= \frac{144 \times 14.334}{53.34 \times 529.6}$$

$$= 0.073077 \text{ lb.}$$

Then

$$z = \frac{M_{steam}}{M_{air}} = \frac{0.001145}{0.073077} = 0.015669$$

Substituting

$$\frac{k_m}{k_m - 1} = \frac{k + \frac{0.14z}{1 + 1.01z}}{k - 1}$$

$$= 3.5051$$

Substituting in

$$W = \frac{k}{k-1} p_1 V_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} - 1 \right]$$

$$= 3.5051 \times 14.7 \times 144 \times 13.4 \left[\left(\frac{150}{14.7}\right)^{.2853} - 1 \right]$$

$$= 93237 \text{ ft. lb.}$$

Comparing this with the result obtained in Case (1) shows that only an error of 0.06 per cent occurs due to the normal moisture in the air. Thus we may safely say that normal moisture in the air does not affect appreciably the work of the cycle.

Case (3). The effect of introducing water into the cylinder. When water is introduced into the cylinder the working fluid is a

mixture of air and vapor with an excess of water. As the compression proceeds the moisture content of the mixture continually changes. It is assumed that the constitutents in the cylinder undergo a simple adiabatic change of state, in being compressed from a pressure p_1 to final pressure p_2, that is, we assume that there is no change of entropy during the change of state. Again assuming that the steam in the mixture does not become superheated, the final temperature T_2 of the mixture must be the saturation temperature corresponding to the partial pressure p''_2 of the steam. The determination of the final state of the mixture involves the determination of two unknown quantities; namely, the partial pressure p''_2 and the quality x_2 of the saturated vapor.

In terms of the temperature and pressure, the entropy of a unit weight of air is given by the expression

$$s = c_p \log_e T - AB \log_e p + s_o$$

hence for the mixture we have

$$S = M_1(c_p \log_e T - AB \log_e p') + M_2 \quad s' + \frac{xr}{T} \quad + S_o \qquad (1)$$

As the constant S_o disappears when the difference of entropy between the two states is taken, it may be ignored in the calculation.

Let S_1 denote the entropy of the initial state. Then since the entropy remains constant, we have

$$S_1 = M_1(c_p \log_e T_2 - AB \log_e p'_2 \,) + M_2 \quad s'_2 + \frac{x_2 r_2}{T_2} \qquad (2)$$

In Equation (2), S_1, M_1, M_2 , and the coefficients c_p and AB are

known, as is the final pressure p_2. The partial pressures p'_2 and p''_2, the quantity x_2, and the temperature T_2 are unknown. However T_2 depends upon p''_2, and p'_2 is found from the relation $p'_2 + p''_2 = p_2$ when p''_2 is determined. Denoting the final volume by V_2, we have

$$V_2 = \frac{M_1 B T_2}{p'_2} = M_2 x_2 v''_2$$

whence

$$x_2 = \frac{M_1 B T_2}{M_2 p'_2 v''_2} \tag{3}$$

Inserting this expression for x_2 in (2), we have finally

$$S_1 = M_1(c_p \log_e T_2 - AB \log_e p'_2) + M_2 \left[s'_2 + \frac{M_1}{M_2} \cdot \frac{Br_2}{p'_2 v''_2} \right] \tag{4}$$

In this equation p'_2 is the only unknown. The solution is most easily effected by the "cut and try" method.

The external work of compression is equal to the change of energy. Hence, using the general expression for the energy of the mixture, we have

$$AW = M_1 c_v (T_1 - T_2) + M_2 (q_1 - q_2 + x_1 \rho_1 - x_2 \rho_2). \tag{5}$$

For comparison with the cases of dry air and moist air let us take a concrete example.

Example. Let us assume that water be injected into the cylinder at the beginning of compression so that the weight of the water shall be twice that of the air. Again take the air under the same conditions as in Case (1). In order to fill the volume 13.4 cu. ft. with a mixture of two parts water, by weight, to one of air, we shall need 1.9792 lb. of water and 0.9896 lb. of air. Assume that the air is initially at 70° F., atmospheric pressure, and is compressed to 150 lb. per sq. in.

From the steam table the partial pressure of the water vapor corresponding to 70° F. is 0.3625 lb. per sq. in.; hence, the partial pressure of the air is 14.334 lb. per sq. in. The initial quality x_1 is found from the equation

$$V_1 = \frac{M\ BT}{p_1'} = M_2 x_1 v_1''$$

whence

$$x_1 = \frac{V_1}{M_2 v_1''} = \frac{13.4}{1.9792 \times 871} = .00776.$$

For the entropy of the mixture we obtain from (1), neglecting the constant S_0

$$S_1 = 0.9896(0.24 \log_e 529.6 - 0.0686 \log_e 14.334)$$

$$+ 1.9792(0.0745 + \frac{1052.3 \times 0.00776}{529.6}$$

$$= 1.4868$$

Substituting values from the steam tables in equation (4) we get, by the "cut and try" method: $p_2'' = 1.446$ lb. per sq. in. Therefore

$p'_2 = 150 - 1.446 = 148.554$ lb. per sq. in. Then from the steam tables at this pressure, $t_2 = 114.5°$, $T_2 = 574.1°$, $q'_2 = 82.42$, $r_2 = 1027.5$, $p = 964.5$, and $v''_2 = 235$. The final quality is

$$X_2 = \frac{M_1BT_2}{M_2P'_2V} = \frac{53.34 \times 574.1}{2 \times 148.554 \times 144 \times 235} = .00304$$

That is, some of the water vapor is condensed during compression.

The external work is

$$W = 778 \Big[0.9896 \times 0.17(70 - 114.5) + 1.9792(36.08 - 82.42 + 0.00776 \times 994 - 0.00304 \times 964.5 \Big]$$
$$= 69,825 \text{ ft. lb.}$$

The volume of the mixture at the end of compression is

$$V_2 = \frac{M_1BT_2}{p'_2} = \frac{0.9896 \times 53.34 \times 574.1}{148.554 \times 144} = 1.416 \text{ cu. ft.}$$

and the work of expulsion is therefore

$$1.416 \times 150 \times 144 = 30,596 \text{ ft. lb.}$$

The work of admission is equal to

$$14.7 \times 144 \times 13.4 = 28,294 \text{ ft. lb.}$$ which is negative.

Then the total work is

$$69,825 + 30,596 - 28,294 = 72,127 \text{ ft. lb.}$$

A comparison of this result with that obtained in the use of dry air, Case (1), shows that there is a saving of 22.6 per cent in the work of the cycle. A considerable saving would be expected since the introduction of water into the cylinder appreciably decreases the

final volume.

Without the injection of water the volume is given by

$$13.4 \text{ x } \frac{14.7}{150}^{\frac{1}{1.4}} = 2.546 \text{ cu. ft.}$$

When water is injected the volume from Case (3) is 1.416 cu. ft. The decrease of volume, then, is 44.5 per cent.

V. CONCLUSION.

The effect of normal moisture upon air compressor performance is so slight that it may be neglected, as the work of the cycle, which is the determining factor, is changed but little. Since in gas engine performance, the moist air affects the volume of the working cylinder, hence the power developed, we must here take it into account and increase the volume in order to allow for that space occupied by the water vapor.

However, when water is introduced into the cylinder in air compression a marked saving in work and final volume is obtained. This saving increases with the increase in the amount of water introduced and approaches a maximum with perfect isothermal compression, which in this case amounts to 29.3 per cent. This isothermal compression is a condition actually obtained in some plants which compress air by the direct action of falling water.

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